VISCOMETERS

The commercial value of numerous fluids produced industrially depends strongly on their viscosity. That is the case when viscosity has a direct effect on how well the fluid performs in its intended application. For example, viscosity plays a significant role in how effectively paint adheres to a wall, and in the uniformity of the coating. Viscosity also plays a key role in the effectiveness of a lubricant in reducing friction between surfaces, in the power required for pumping sludge from waste reclamation facilities, and so on. The quality of a number of products is specified in terms of well-defined values of viscosity. Such is the case for lubricants, where stringent viscosity specifications have been established since the early 1920s, and also for numerous industrial polymers, as well as inks, paints, and other coating materials.

Definition of Viscosity

When a force is applied to a fluid, the molecules of the fluid are displaced from their positions and move past each other. A velocity gradient is established because molecules located at various points develop different velocities in response to the applied force. This causes a deformation of the fluid: regions of high velocity can be easily imagined to cause a local stretching of the material with respect to regions of lower velocity. Clearly, the extent of the deformation can be quantified in terms of the observed variations of velocity at different locations, or more precisely, in terms of the developed velocity gradient. In some fluids the applied force causes only minor velocity changes, while for other fluids the same force may cause very large changes. The former are commonly referred to as *thin* fluids because they deform easily, posing little resistance to the applied force, while the latter are called *thick* because they are more difficult to deform. If the force is ap-

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*.

plied to a fluid surface parallel to the direction in which the material is flowing, it is known as a *shear force,* and the rate at which it causes the fluid to deform is called the *shear rate.* The shear rate produced by a given shear stress depends upon the *viscosity* of the fluid, which is a measure of its thickness. In qualitative terms, one may say that the viscosity of a fluid is the property that determines the extent to which the material resists deformation.

A quantitative definition of viscosity is more easily formulated in terms of the system shown in Fig. 1, where a fluid is contained between two parallel plates. A force F is applied to the upper plate, while the lower plate is kept stationary. As a result, the top plate and the fluid layer immediately next to the plate move with a velocity u, while the fluid layer next to the bottom plate remains at zero velocity. Clearly, the applied force has caused a deformation pattern in the fluid. If the surface area of the fluid is A, then the force per unit area, $\tau = F/A$, is called the *shear stress.* Furthermore, the gradient of the velocity field, $\dot{\gamma} = du/dy$, is called the *shear rate* (also called *shear strain rate*), and is interpreted as a measure of the rate of deformation of the fluid. The viscosity of a fluid is denoted by the symbol η, and is defined as the ratio of the shear stress to the shear rate,

$$\eta = \frac{\tau}{\dot{\gamma}} \tag{1}$$

where in SI units the viscosity η is measured in pascal-seconds (Pa · s), the shear stress τ is measured in pascals (newtons per square meter), and the shear rate $\dot{\gamma}$ is measured in reciprocal seconds (s^{-1}). A common unit of viscosity is the *poise* (P), and 10 P = 1 Pa · s. In turn, the *centipoise* (cP) is defined so that 100 cP = 1 P. The *kinematic viscosity* $\nu = \eta/\rho$ is defined as the ratio of the viscosity to the density of the fluid and is measured in units of m^2/s. For the velocity field shown in Fig. 1 it is clear that the shear rate is given by $\dot{\gamma} = u/L$, where L is the distance between the two parallel plates; therefore, application of the general definition (1) to this simple flow system yields that the viscosity is given by the expression $\eta = L\tau/u$. For more complicated shear flow systems, the viscosity is often determined by imposing a shear stress τ, measuring the resulting shear rate $\dot{\gamma}$, and then taking the ratio of these quantities to calculate the viscosity as prescribed by the general definition given by Eq. (1).

In general, the viscosity is a function of the temperature, pressure, and chemical composition of the fluid. The viscosity is also affected by the physical composition of the material, namely, the number and type of different thermodynamic phases present. For example, a multiphase system consisting of water (liquid) and air (gas) will have a very different viscosity from that of the homogeneous water system or the homogeneous gas system, depending upon the relative concentrations of air and water in the multiphase mixture. The viscosity of common fluids is available in tables of physical properties of materials. For example, at 20°C and 1 atm (10^5 Pa) of pressure the viscosity of air is approximately 1.8×10^{-5} Pa · s, while the viscosity of water is 1.0×10^{-3} Pa · s, and of ethyl alcohol is 1.8×10^{-3} Pa · s. Some materials have exceedingly high viscosities; for example, molten glass at 500°C has a viscosity of 1.0×10^{40} Pa · s. In practical applications fluids are exposed to a wide range of shear-rate values. For example, lubrication oils operating between rotating metal walls in an automobile axle can be exposed to shear rates as large as 10^7 s^{-1}, whereas the sedimentation of particles initially suspended in a fluid exposes the walls of the falling particles to shear rates as small as 10^{-6} s^{-1}.

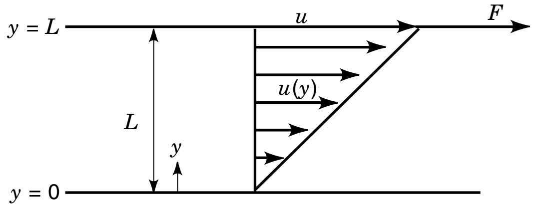

Figure 1. A fluid is sheared between two parallel plates separated by a distance L. While the lower plate is stationary, a force F is applied to the upper plate, causing a deformation in the velocity field such that the top fluid layer flows with velocity u while the bottom layer has velocity zero. The surface area of upper plate is A.

Newtonian and Non-Newtonian Fluids

A fluid is said to be *Newtonian* if the viscosity remains constant for all shear rates at constant temperature, pressure, and chemical composition of the material. Many common fluids exhibit Newtonian behavior at room temperature. However, other fluids of interest, such as polymer melts, coatings, foods, and many multiphase mixtures, are non-Newtonian in that the viscosity is a function of shear rate. Non-Newtonian fluids can be time-independent or time-dependent, depending on whether the viscosity at constant shear rate remains constant or changes with respect to time. Time dependence of viscosity can be the result of chemical changes (e.g., polymer degradation) or structural changes in multiphase systems (e.g., ketchup, mayonnaise) that occur during shearing. Finally, some non-Newtonian fluids exhibit elastic shear properties, that is, part of the deformation produced by the stress can be recovered when the stress is removed. Such materials are called *viscoelastic* fluids. The response of a viscoelastic fluid to shear is strongly dependent on the shear rate. Obviously, all viscoelastic fluids are non-Newtonian, and a complete description of their response is extremely complex. However, in general the viscous portion of the response can be characterized separately from the elastic component.

Figure 2 illustrates several relevant types of viscous responses normally encountered for time-independent fluids. The constant slope of the shear-stress versus shear-rate curve shown in the curve for a Newtonian fluid reflects the fact that the viscosity is constant for all shear rates. Simple homogeneous fluids and most lubricants are Newtonian. If the viscosity decreases with increasing shear rate, the fluid is described as *pseudoplastic;* if it increases, *dilatant.* Nearly all polymers and polymer solutions are pseudoplastic, while many multiphase materials are dilatant. For some fluids, a certain level of shear stress, called the *yield stress,* must be exceeded before the fluid begins to flow. After this stress is exceeded, the fluid may behave as a pseudoplastic or dilatant material, or may adopt a behavior similar to a Newtonian material (as is the case of the Bingham plastic behavior shown in Fig. 2). Many food products and pastes exhibit yield stress.

Measurement of Viscosity

A *viscometer* is an instrument used to measure the viscosity of a fluid. These instruments are also called *rheometers,* since

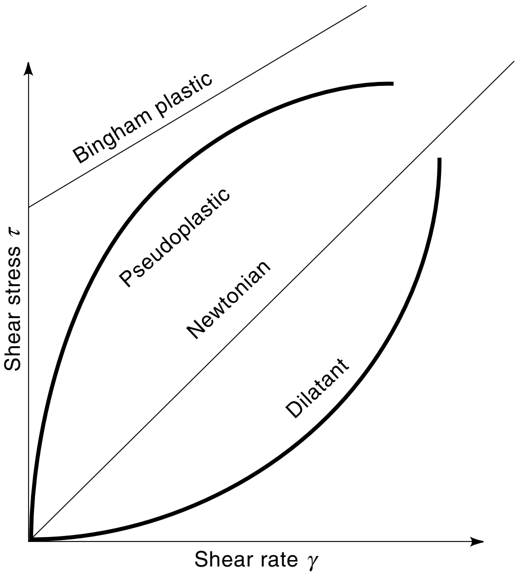

Figure 2. Shape of four typical curves of shear stress versus shear rate for time-independent fluids. The viscosity, given by the ratio of shear stress to shear rate, is constant for Newtonian fluids. Bingham plastics show no deformation for shear-stress values below a minimal nonzero value called the yield stress. Dilatant and pseudoplastic fluids are strongly non-Newtonian materials.

rheology is the science that studies the flow of materials under stress. A viscometer can be used in a laboratory facility, or directly in the industrial production line where the fluid of interest is processed. The laboratory method is an *off-line* technique which often involves a time delay because the sample of the fluid must be transported from the production facilities to an adjacent laboratory environment. The off-line measurement has the advantage that the viscosity can be determined under highly controlled temperature and pressure conditions, and for a wide range of shear rates, resulting in a more accurate characterization. The delay associated with off-line measurements, however, can result in poor process-control performance, and the production of large quantities of material of undesirable characteristics. Furthermore, factors such as corrosiveness and toxicity of the fluid often complicate the use of off-line methods. Also, for materials such as slurries, the rheology of which is important for many mineral processing operations, off-line measurements may be nonrepresentative of the actual sample in process, due to particle settling and the possible occurrence of irreversible particle interactions such as coalescence and agglomeration.

When measurement delays cannot be tolerated, the viscometer can be installed directly in the path of the fluid being processed (*in-line* installation) or in a bypass line that is directly connected to the main path of the fluid (*on-line* installation). Diagrams illustrating in-line and on-line deployment of a viscometer are shown in Fig. 3. Both in-line and on-line instruments aid in maintaining desired product quality. In-line viscometers measure the viscosity at the temperature, pressure, and flow rate of the flowing fluid. Furthermore, since the process conditions (temperature, pressure, concentration, etc.) are usually measured and values are available, no extra hardware and control effort in addition to the in-line viscometer is needed to characterize the sample being tested. However, the sensor is subject to harsh process conditions and disturbances in the process line may damage the sensor. Also, testing is limited to the process conditions. A good instrument must allow for the fact that process streams are often subject to perturbations in temperature, pressure, and flow rate, which can have a great influence on the viscosity measurement. An additional disadvantage of an in-line installation is that the process flow must be interrupted when the viscometer requires service, causing a discontinuity in the production rate and possibly affecting processing equipment located downstream.

In contrast, on-line installations have the advantages that instrument service and repairs can be done by isolating the bypass line without affecting the flow of the process fluid. Furthermore, the temperature and flow rate of the sampled fluid can be more closely controlled with the installation of small heat exchangers and flow valves, which can improve the accuracy of the viscosity measurement. However, on-line installations often require a higher capital investment because of the additional cost involved in the installation of the bypass lines, flow valves, and heat exchangers.

In the food and dairy industries, where hygiene is a dominant concern, in-line installations are often avoided because they introduce an additional maintenance overhead due to the need for frequent cleaning and disinfection. However, in many applications in-line installations are necessary in order to maintain adequate measurement conditions, such as laminar flow.

The desirability for in-line or on-line measurement of viscosity, particularly for multiphase materials and for materials from natural sources, has been recognized for at least 20 years. Also, the economic incentives for in-line blending of fluids to reduce inventory and labor costs, for better control of product uniformity, and for increased rates of production have been recognized, and are expected to drive the continuous development of new viscometers and the identification of new applications for the instruments. Implementation has been retarded by the complexity and costs of the instruments, by the range of design modifications necessary for general application, and by the moderate resources available to most viscometer manufacturers, who are constrained by the fact

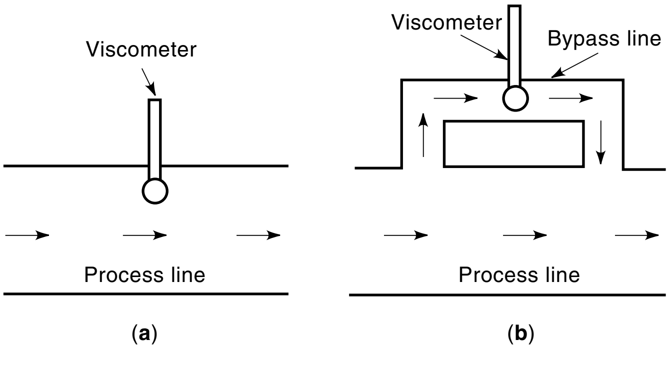

Figure 3. Viscometers deployed in an (a) in-line and (b) on-line fashion. In-line and on-line instruments are designed for use in the production environment and measure the viscosity of the fluid as it flows through its processing lines. The on-line configuration can include flow-control valves and heat transfer equipment to provide stable thermodynamic conditions on the bypass line. Viscometers design for use in laboratory facilities are known as off-line instruments.

that any particular design will address only a limited market segment. Nevertheless, several in-line and on-line instruments are currently available and are beginning to be used with increasing regularity.

Viscometers can be grouped into the following major types according to the principle used for measurement: (1) falling-element, (2) rotational, (3) pressure-flow, and (4) vibrational. Viscometers of these four types may be designed for use in off-line, in-line, or on-line deployment modes. Each measuring principle involves specific governing equations that relate the viscosity to measurable parameters. Other principles of measurement are possible, but they are less common and are therefore not discussed here. A viscometer must be designed and operated so that flow within the instrument is laminar. In all cases, the approach consists in subjecting the fluid to a known or controlled shear rate and measuring the shear stress, or vice versa.

For accurate viscosity measurements, most instruments require calibration against fluids of known viscosity. This is most often performed with commercially available standard oils that are Newtonian fluids of precisely known viscosity. The calibration procedure consists in measuring the viscosity of the standard fluid and then adjusting one or more parameters in the governing equations until the instrument readings match closely the viscosity of the standard.

Because of specific mechanical constraints, each instrument has limits on the shear rates and shear stresses that can be attained; hence, particular care must be taken in the selection of an instrument for a given application. This is most particularly important for non-Newtonian fluids, since the viscosity may be a strong function of shear rate. Furthermore, viscosity is a bulk transport property, and care must be exercised to ensure that measurements are free of artifacts introduced by the instrument geometry; this concern is particularly significant for the measurement of the viscosity of multiphase materials.

MAJOR TYPES OF VISCOMETERS

This section presents various types of viscometers grouped according to the principle of measurement used, and discusses the underlying physical relationships and governing equations associated with each instrument. For reference, Table 1 lists several commercial viscometers available for off-line use, and Table 2 lists instruments designed for in-line or on-line use. Table 3 gives contact information for several major viscometer manufacturers.

Falling-Element Viscometers

Falling-element viscometers involve dropping a solid weight inside a fluid contained in a vessel and measuring the terminal velocity of the weight as it falls. The viscosity is then determined from a governing equation that uses the terminal velocity as a primary input, and that also makes use of a number of known variables such as the weight and dimensions of the falling element, the densities of the element and of the sample fluid, and other geometric factors. The shear rate produced is the result of a combination of the drag force on the moving surface of the falling element and the pressure flow due to the motion of the fluid as it is displaced by the falling element. Therefore, even though the shear rate is significant in one direction only, the flow pattern is nevertheless complex. The most common falling-element viscometers utilize a cylinder or a sphere as weights. The Gardener viscometer uses a perforated disk as the falling element, but although this instrument was widely used in the past, it is now obsolete (1).

Although falling-element viscometers are predominantly used as off-line instruments, several instruments are now available commercially for utilization in an on-line mode with clean, Newtonian fluids. In these instruments a sample from the flowing stream is drawn into the viscometer's vessel by pumping. Then the sample is isolated from the flowing stream by closing an inlet valve, and a measurement of the terminal velocity of the falling element is taken. When the measurement has been completed, the sample is discharged back into the flowing stream, a new sample is introduced, and the process is repeated. An example of such type of on-line falling-element viscometer is an instrument marketed by Cambridge Instruments.

Table 1. List of Selected Off-Line Viscometers That Are Commercially Available

Viscometer Type	Manufacturers	Specific Features	Target Industries
Capillary	Goettfert	Shear-stress control.	Polymer industry
	Contraves	Shear-stress control.	
	Instron	Shear-rate control.	
	Shimidzu	Shear-rate control.	
Rotational	Bohlin Rheometrics Haake Contraves Brookfield Rheologica	Vary depending upon geometry of viscometer as well as fluid properties. Limited to lower shear rates.	Used in all industries covering a wide range of viscosities
Vibrational	Nametre	Newtonian fluids only limited to one frequency. Very broad viscosity range.	
Sliding element	Cambridge	Fluid need not be Newtonian; used mainly for quality control.	Petroleum, specialty chemicals
	Stony Brook Scientific	Fluid must be particulate-free.	

Table 2. List of Selected Viscometers Designed for In Line or Off Line Use

Viscometer Type	Manufacturers	Specific Features	Target Industries
Capillary	Rheometrics Seiscor Micro Motion Kayeness	Applicable to non-Newtonian and high-viscocity fluids. Pressure drop required.	Polyers, food, petroleum, pulp and paper
Rotational	Brookfield BTG	Applicable to non-Newtonian fluids. There are moving parts, and provisions are needed for minimizing the effect of drag flow.	Pulp and paper, food, coatings
Vibrational	Nametre Dynatrol BTG	Wide viscosity range. Large volume of fluid required for accurate measurement.	Broad applications
Sliding element	Cambridge	Relatively inexpensive. Only clean Newtonian fluids with low viscosity (<200 cP) for accurate measurement.	Petrolum and marine fuels, simple solutions

Falling-element devices can be used to measure the viscosity of Newtonian fluids accurately, but are of limited value for non-Newtonian fluids. The problem is that these instruments operate at a fixed shear rate, and therefore cannot describe the shear-rate-dependent viscosity of non-Newtonian fluids. Moreover, the governing equations for the physics that describe the fall, including a situation where the falling element is off center, have not been solved successfully for non-Newtonian fluids. Therefore, use of these devices should be limited to measurements under conditions where the fluid exhibits Newtonian behavior.

Falling-Cylinder Viscometer. Falling-cylinder viscometers are the most commonly used falling-element viscometers. These devices consist of a solid cylinder that falls vertically through a hollow cylindrical vessel of larger radius (2). The sample fluid contained within the hollow vessel is sheared by the solid cylinder, which falls downward over a fixed vertical distance under the influence of gravity, or a combination of gravity and an externally applied force (3). The time required for this distance to be traversed is a function of the fluid's viscosity. As with all falling-element viscometers, the higher the viscosity of the fluid, the lower the velocity of the falling element. When the relative gap width, defined as $(r_0 - r_c)/r_0$, is very small, the viscosity of the fluid can be calculated using the relationship (4)

$$\eta = \frac{F(r_0 - r_c)}{2\pi r_c h u} \tag{2}$$

where F is the force driving the fall of the element, r_0 is the radius of the cylindrical vessel, r_c is the radius of the falling cylinder, and u is the terminal velocity of falling cylinder. The terminal velocity u is easily determined by measuring the time the falling cylinder takes to travel between two reference points in the vessel separated by a known distance. This measurement can be made using optical or electrical detectors that sense the instant when the falling element passes through the reference points. When the cylindrical element falls under the influence of gravity alone, the force shown in Eq. (2) is given by the expression $F = \pi r_c^2 h(\rho_c - \rho_f)g$, where h is the length of the falling cylinder, u is its terminal velocity, ρ_c is its density, ρ_f is the density of sample fluid, and g is the gravitational acceleration. The cylinder's fall can also be driven by electromagnetic forces provided by an electrical coil wrapped around the outside wall of the vessel. In that case the force F used in Eq. (2) must include the prescribed electromagnetic force in addition to the gravitational force. Equation (2) is valid for non-Newtonian as well as Newtonian fluids, provided that the relative gap width is small.

The accuracy of the viscosity measurement determined by the falling-cylinder method may be degraded by several undesirable effects. In particular, the following potential problems are of relevance: (1) end effects in the flow pattern near the top or the bottom of the cylindrical vessel can lead to significant errors in the viscosity measured, and must be taken into account; (2) tumbling may occur while the cylinder is falling through the fluid; (3) a horizontal shifting of the solid cylinder may result in an off-center descent in the vessel. These problems can be alleviated to a certain extent by decreasing the radius of the falling cylinder while increasing its length (2). The net objective is to achieve a larger value of the length-to-diameter ratio (L/D) of the instrument, so that horizontal shifts and end effects are minimized.

Falling-Sphere Viscometer. Falling sphere viscometers operate on the principle of measuring the terminal velocity of a solid sphere as it falls through a sample fluid contained in a cylindrical vessel. As in the case of the falling cylinder, the terminal velocity is simply determined from the measurement of the time taken by the sphere to traverse a fixed distance (5). The viscosity can be calculated from Stokes's equation (6)

$$\eta = \frac{2}{9}\frac{(\rho_s - \rho_f)r_s^2 g}{u} \tag{3}$$

where ρ_s is the density of the sphere, ρ_f is the density of the fluid, r_s is the radius of the sphere, u is the terminal velocity of the sphere, and g is the gravitational acceleration. Stokes's equation is applicable when (1) the sample fluid is Newtonian and (2) the radius of the sphere is much smaller than the radius of the cylindrical vessel.

Rotational Viscometers

Rotational viscometers utilize the principle of shearing a fluid between two walls (one moving in a rotational motion and one stationary) to create a velocity profile in the liquid as well as

Table 3. Contact Information for Selected Viscometer Manufacturers

Company	Laboratory Models: Features	In-Line/On-Line Models: Features
Bohlin Instruments Inc. 2540 Rt. 130 Cranbury, NJ 08512 USA Ph: (609) 655-4447 Fax: (609) 655-1475 http://www.bohlin.com	*Visco-88:* Coaxial cylinders Cone and plate	
Brookfield Engineering Labs Inc. 240 Cushing St. Stoughton, MA 02072-2398 Ph: (800) 628-8139 Fax: (617) 344-7141 http://www.brookfieldengineering.com	*Model DVI+, DVII+:* Coaxial cylinders Cone and plate *Model SSB:* Coaxial cylinders *CAP 1000, CAP 2000:* High-shear-rate visc. Cone and plate	*TT 100, TT 200:* Coaxial cylinders *TT 100VS:* Variable speed *TT 220, PVT 230:* Control system
BTG 2364 Park Central Blvd. Decatur, GA 30035-3987 Ph: (770) 981-3998 Fax: (770) 987-4126 http://www.btghome.com		*VISC 21 5E:* Parallel-plate rotation *VISC 2000E:* Coaxial cylinders *MBT 4000:* Oscillating plate
Cambridge Instruments 196 Boston Ave. Medford, MA 01255 Ph: (781) 393-6500 Fax: (781) 393-6515 http://www.cambridge-applied.com	*ViscoLab 3000:* Electromagnetic det.	*SPC 301, 311:* Falling cylinder *SPC 372J:* Falling cylinder Low flow rate jacket sensor *SPC 392:* Falling-cylinder flange *SPC 401, 501:* Falling cylinder
Dynatrol Div., Automation Products, Inc. 3032 Max Roy St. Houston, TX 77008 Ph (USA and Canada): (800) 231-2062 Fax: (713) 869-7332		Vibrating probe
Geottfert Inc. 488 Lakeshore Parkway Rock Hill, SC 29730 Ph: (803) 324-3883 Fax: (803) 324-3993 http://www.goettfert.com	Capillary rheometers Mooney viscometers	Capillary rheometers
Haake 53 W. Century Rd. Paramus, NJ 07652 Ph: (800) 631-1369 Fax: (201) 265-1977 http://www.haake-usa.com	*Viscotester, VT 550:* Rotational viscometer, varying geometries	
Instron Corporation 100-TR Royall St. Canton, MA 02021-1089 Ph: (800) 373-6978 Fax: (781) 575-5751 http://www.instron.com	Capillary rheometers	
Kayeness Polymer Test Systems 115 Thousand Oaks Blvd., Suite 101 P.O. Box 709 Morgantown, PA 19543 Ph: (610) 286-7555 Fax: (610) 286-9396 http://www.dynisco.com	Capillary rheometers	Capillary rheometers Slit rheometers
Micro Motion, Inc. 7070 Winchester Circle Boulder, CO 80301 Ph: (303) 530-8400 Fax: (303) 530-8596 http://www.micromotion.com		*Coriolis flow meter:* Measures pressure drop and flow rate

Table 3. *Continued*

Company	Laboratory Models: Features	In-Line/On-Line Models: Features
Nametre 101 Liberty St. Metuchen, NJ 08840 Ph: (732) 494-2422 Fax: (732) 494-8916 http://www.nametre.com	Vibrational Torsional oscillation Spherical and cylindrical	*Viscoliner:* Vibrational Torsional oscillation Spherical and cylindrical
Norcross 255 Newtonville Ave. Newton, MA 02158-1898 Ph: (617) 969-7020 Fax: (617) 969-3260 http://www.viscosity.com		*In-Line Viscometers M10, M20, M24, M50:* Atmospheric-pressure viscometers to be mounted on tanks
Rheometrics Scientific Inc. One Possumtown Road Piscataway, NJ 08854 Ph: (732) 560-8550 Fax: (732) 560-7451 http://www.rheosci.com	Dynamic stress rheometer Differential thermal rheometer Bench-top viscometers	

to impose a force on the stationary wall. The resulting type of flow is known as *drag flow*. The walls, or boundaries, are arranged with specific geometries that allow the viscosity of the liquid contained between them to be determined through measurement of the force applied on the stationary wall. The best-known drag-flow instruments are the cone-and-plate viscometer, the parallel-plate viscometer, and the coaxial-cylinder viscometers.

Cone-and-Plate Viscometer. The cone-and-plate viscometer is a rotational drag-flow device in which the sample fluid is sheared between a rotating cone and a fixed plate (Fig. 4) (2). The cone is usually situated above the plate, with a point of contact at the vertex of the cone and the midpoint of the plate (7). In order to achieve a shear rate that depends only on the direction of rotation (i.e., that is independent of the radial direction), the angle between the cone and the plate surfaces is small (usually smaller than 3°) (8).

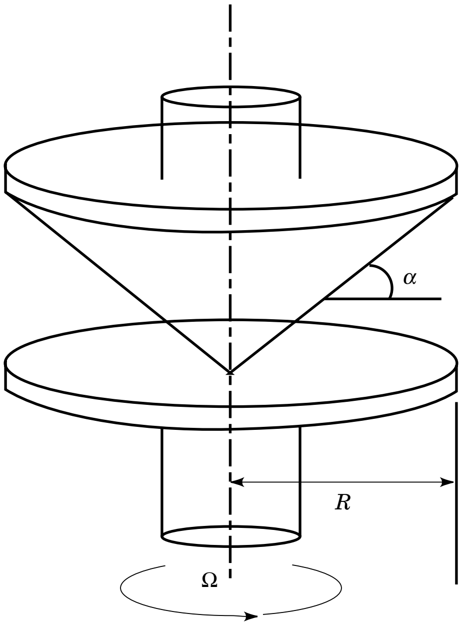

Figure 4. Schematic of a cone-and-plate viscometer geometry where the plate rotates at a constant angular velocity while the cone is fixed. The angle between the cone and plate is typically smaller than 3°. The fluid is confined between the surfaces of the cone and the plate.

At constant angular velocity, the shear stress in the fluid is proportional to the torque exerted by the fluid on the cone. For small angles between the cone and the plate surface, the shear rate within the fluid is constant. The viscosity of the sample at a particular shear rate can be calculated as (3)

$$\eta = \frac{3\tau\alpha}{2\pi R^3\Omega} \tag{4}$$

where τ is the torque exerted on the cone, α is the angle between the cone and plate, Ω is the rotational velocity of the cone, and R is the radius of the cone. Equation (4) is valid for all incompressible fluids, provided there is no slip at the surface (2).

Cone-and-plate viscometers are easy to operate; however, there are several sources of error that can affect the measurement, including (1) fluid inertia and secondary flow, (2) edge effects, (3) nonuniformity of the shear field due to a large cone angle, (4) viscous dissipation, and (5) nonideal geometry. Collyer and Clegg (2) or other pertinent references should be consulted for information on appropriate procedures to avoid or minimize these errors. The operation of cone-and-plate viscometers is restricted to creeping flow conditions; therefore their use is limited to low shear rates, typically smaller than 20 s^{-1}.

Parallel-Plate Viscometer. A parallel-plate viscometer is simply a cone-and-plate viscometer in which the angle between the cone and the plate is zero and there is no longer a contact point between the two surfaces. This instrument is particularly useful for the measurement of the viscosity of multiphase materials; however, it is restricted to measurements at very low shear rates, and the shear rate is no longer constant throughout the fluid. In a given sample, the viscosity at a particular shear rate (the shear rate at the edge of the fluid) can be calculated as (3)

$$\eta = \frac{\tau h}{2\pi \Omega r^4} C_{\mathrm{F}} \tag{5}$$

where τ is the torque exerted on the plate, Ω is the angular velocity of the moving plate, r is the plate radius, h is the distance of separation between plates, and C_{F} is a correction factor defined as

$$C_{\mathrm{F}} = 3 + \frac{d \ln(\tau/2\pi r^3)}{d \ln(\Omega r/h)} \tag{6}$$

In general, the parallel-plate viscometer is subject to the same limitations as the cone-and-plate viscometer.

An instrument for on-line viscosity measurement using parallel-plate or cone-and-plate geometries is available through BTG. This instrument may yield relative viscosity values that are useful for process control purposes, but it is unlikely to yield accurate on-line measurements, since the flow does not have a free surface at the boundary between the plates. For measurement accuracy there must be virtually no flow through the gap between plates during a measurement; however, some flow is necessary to make measurements of viscosity periodically on fresh samples of the flowing fluid.

Rotating-Cup Viscometer. This viscometer consists of two coaxial cylinders that contain the fluid to be measured in the annular gap between them. One cylinder (called the *stator*) is held stationary while the other cylinder (called the *rotor*) is rotated. Two configurations are possible. In one configuration the cup rotates inside the hollow stator, and in the other the immobile stator is located inside the rotating cup. The fluid being measured is sheared in the annular gap. The shear stress can be directly determined by measuring the torque delivered by the motor that drives the rotating cup, or by measuring the torque required to hold the stator immobile. The shear rate can in turn be directly determined by the rotational speed of the cup. For the configuration that features the stator positioned inside the cup, the shear stress and shear rate are given by

$$\tau = \frac{1}{2\pi R_{\mathrm{o}}^2 L_{\mathrm{c}}} T \tag{7}$$

$$\gamma = \frac{4\pi C_{\mathrm{F}}}{1 - (R_{\mathrm{i}}/R_{\mathrm{o}})^2} N \tag{8}$$

where T is the measured motor torque, N is the rotational speed of the cup measured in revolutions per second, the geometrical parameters R_{i} and R_{o} are the inner and outer radii of the gap, and L_{c} is the effective length of the stator. The parameter C_{F} is an experimental curvature–flow-index correction factor that takes into account the fact that the curved walls of the gap are not exactly parallel plates and that the fluid may be non-Newtonian (9–12). Using the viscosity definition (1), the working equation for the rotating-cup viscometer reduces to

$$\eta = \frac{1 - (R_{\mathrm{i}}/R_{\mathrm{o}})^2}{8\pi^2 R_{\mathrm{o}}^2 L_{\mathrm{c}} C_{\mathrm{F}} N} T \tag{9}$$

When the correction factor is arbitrarily set equal to $C_{\mathrm{F}} = 1$, ignoring the effects of curvature, then Eq. (7) yields the *apparent shear stress,* Eq. (8) gives the *apparent shear rate,* and Eq. (9) the *apparent viscosity.* For accurate viscosity determinations, the instrument is calibrated with standard fluids to determine effective length L_{c} for use in Eq. (9) (4,13).

A typical approach for determining viscosity using the governing Eq. (9) is to first fix the rotational speed N at a desired operating value, and then rewrite Eq. (9) in the form

$$\eta = \phi T \tag{10}$$

where ϕ is a parameter determined experimentally by measuring the torque attained when the instrument is loaded with a standard calibration oil of precisely known viscosity. Equation (10) is then used to calculate the viscosity of any fluid at the given rotational speed. Other specialized types of rotational instruments, such as the Stormer viscometer (1), were widely used in the past, but are now superseded by coaxial cylinder viscometers for laboratory use.

It must be emphasized that the flow induced within the gap by drag must be laminar. If the inner cylinder is the rotor, the curl in the fluid caused by the rotation of the inner cylinder can induce secondary rotational flows imposed on the laminar flow. This can introduce serious error. Finally, viscous dissipation within the fluid can introduce errors due to temperature changes if the fluid is sheared for extended periods. The useful shear-rate range varies with the instrument and fluid, but is generally limited to 600 s^{-1} to 800 s^{-1} if the inner cylinder is the rotor, and 1000 s^{-1} to 1300 s^{-1} if the outer cylinder is the rotor. Rotational viscometers are popular measurement devices because they require small sample sizes, are reasonably easy to use, deliver accurate measurements if used correctly, and can be used for non-Newtonian as well as Newtonian fluids. Their principal disadvantage is that in order to protect the motor and electronics from the fluid, the moving part uses a seal that may require regular check and maintenance.

A commercial rotating-cup viscometer produced by Brookfield Engineering is shown in Fig. 5. The schematic shown is for an in-line instrument that features a rotating cup and a stator mounted vertically inside the cup while the process fluid flows along a horizontal pipe. Most of the material flows around the external walls of the rotor, bypassing the instrument to reach the outlet port. A fraction of the fluid enters the sampling chamber from the bottom and flows upwards into the measuring gap, where it is sheared by the rotating cup. The measured fluid then leaves the measurement gap by flowing upwards and exiting through openings at the top of the rotor. The pressure flow through the gap superimposes an axial shear-rate component on the rotational component. Care must be exercised to ensure that the stress resulting from pressure flow through the instrument gap is negligible compared to the stress resulting from the drag flow. This can be controlled by varying the bypass area for flow, by varying the total flow rate, or by varying the instrument dimensions.

BTG has also marketed a coaxial cylinder viscometer for in-line or on-line measurements. In the proposed design the entering flow is directed through the gap, which leads to superimposing a large pressure flow stress, unless the flow is interrupted for measurement. With continuous flow, this in-

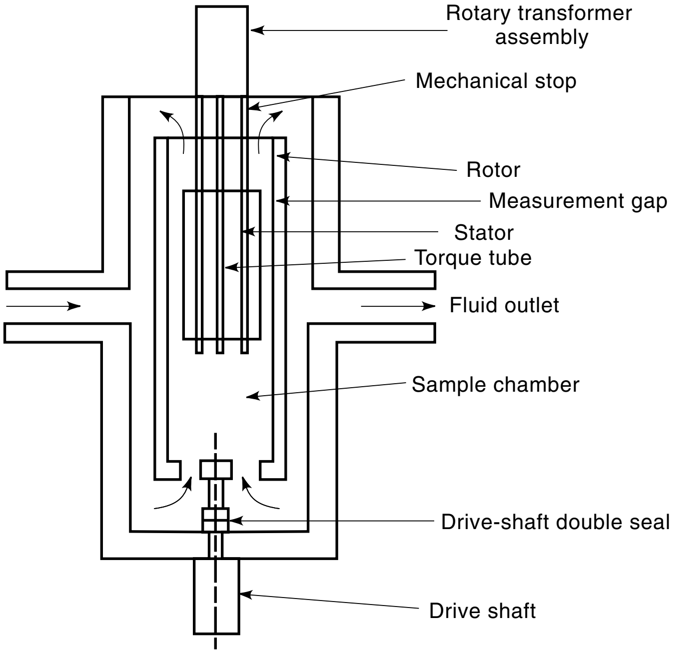

Figure 5. Schematic of an in-line rotational viscometer. The torque required to maintain a specified rotational speed is related to the viscosity of the sample.

strument can give only relative values, even with constant flow rate.

Pressure-Flow Viscometers

Several methods for measuring viscosity are based on the properties of axial flow through a channel, where the flow is driven by the pressure difference between the ends of the channel. Ideally, the pressure difference should be measured for fully developed laminar flow through a channel of circular cross section (i.e., a tube); however, one-dimensional flows through a slit have also been used successfully. Usually, the pressure difference is measured over the entire channel length; nevertheless, this practice is not recommended, because it can introduce errors due to entry and exit effects. These adverse effects can be minimized by using tubes with large L/D ratios.

Pressure-flow viscometers are most often constructed using a *capillary,* which is simply a tube of small diameter. The pressure drop needed to maintain a sustained liquid flow rate can be supplied mechanically (using a pump or a plunger, for example), or simply by the fluid head due to gravity. In the latter case, pressure-flow viscometers allow the determination of only the kinematic viscosity, $\nu = \eta/\rho$, where ρ is the density of the fluid. The viscosity η of the fluid can be found from the measured kinematic viscosity provided that the density of the material is known or is measured using a densitometer. The most common types of pressure-flow instruments include classical capillary viscometers capable of accurate measurements, glass capillary viscometers in widespread use for characterizing Newtonian fluids, and specialized capillary viscometers that have been standardized for use in selected fluids.

Classical Capillary Viscometers. A number of pressure-flow viscometers featuring a capillary tube are available for making accurate viscosity measurements for a wide range of fluids. The laboratory versions of these instruments can be configured in a stress-controlled or a shear-rate-controlled mode, depending on whether the instrument operates at a constant shear stress or at a constant shear rate. For reference, selected instrument manufacturers are listed in Table 1. In response to market demands, a large number of the instruments available commercially have been developed for the study of highly viscous materials. Generally, end effects are minimized by using long capillaries ($L/D > 50$), or by making measurements with capillaries of different lengths and the same diameter and using the results to make appropriate corrections for end effects (14–17). With such techniques accurate measurements of viscosity as a function of the shear rate at the wall of the capillary can be made. When the flow is laminar, the shear rate at the wall of the capillary is given by the expression (3,4,18)

$$\dot{\gamma}_{\mathrm{w}} = \frac{Q}{\pi r^3}\left(\frac{3n+1}{n}\right) \tag{11}$$

with

$$n = \frac{d\ln \tau_{\mathrm{w}}}{d\ln Q} \tag{12}$$

where Q is the volumetric flow rate through the capillary, r is the radius of the capillary, τ_{w} is shear stress at the wall, and $\dot{\gamma}_{\mathrm{w}}$ is shear rate at the wall. The parameter n defined in Eq. (12) is known as the *flow index,* and for Newtonian fluids it takes the value $n = 1$. The shear stress at the wall of the capillary is in turn given by the expression (3,4,14)

$$\tau_{\mathrm{w}} = \frac{r\,\Delta P}{2h + 4rC_{\mathrm{F}}} \tag{13}$$

where ΔP is the pressure drop across the capillary, r and h are respectively the radius and the length of the capillary, and C_{F} is a correction factor that must be determined experimentally. From Eq. (1) it follows that the viscosity is given by the expression

$$\eta = \left(\frac{\pi r^4}{2h + 4rC_{\mathrm{F}}}\,\frac{n}{3n+1}\right)\frac{\Delta P}{Q} \tag{14}$$

An experimental measurement of viscosity using a capillary viscometer consists of measuring the volumetric flow rate Q along with the pressure drop ΔP across the capillary, and then using Eq. (14) to compute the viscosity. The greater the L/D ratio of the capillary, the more accurate the measurement, due to decrease in end affects. In every case, the flow rate through the capillary must be adjusted to ensure laminar flow.

In general, off-line versions of classical capillary viscometers require relatively small volumes of fluid samples, and permit making measurements at shear rates of 30,000 s^{-1} or higher. In most cases, the commercially available laboratory instruments of this type are designed for fluids with high viscosity (typically in excess of 600 cP). Furthermore, laboratory versions of these instruments are typically inexpensive; in contrast, in-line and on-line versions of pressure flow viscometers are expensive, and therefore have found applications in manufacturing operations where there are significant economic incentives to justify the higher capital expenditure, such as in the processing of polymer melts. On-line and in-line instruments are marketed by several providers, including Kayeness and Rheometrics, among others (Table 2).

A recent variation of a capillary viscometer that is being successfully used in a number of on-line applications consists of combination of two sensors, namely, (1) a Coriolis mass-flow meter that measures the density and the mass flow rate of the fluid, and (2) a differential pressure cell that measures the pressure drop across a capillary tube (19). Recognizing that the volumetric flow rate Q and the mass flow rate m are related by $Q = m/\rho$, where ρ is the density, it is possible to rewrite Eq. (14) in the form

$$\eta = \phi \frac{\rho\,\Delta P}{m} \tag{15}$$

where ϕ is an instrument constant that in principle is equal to the factor inside the parentheses on the right-hand side of Eq. (14). In practice, ϕ is determined experimentally for the specific fluid of interest, and may be a function of temperature. A capillary–Coriolis viscometer arrangement similar to that marketed by Micro Motion Inc. is shown in Fig. 6. It is preferred that the pressure drop be measured across a straight tube upstream or downstream of the Coriolis meter to minimize turbulence and end effects. For common combinations of Coriolis and pressure-cell sensor pairs, the instrument can operate in a range of viscosities differing by a factor of 6.

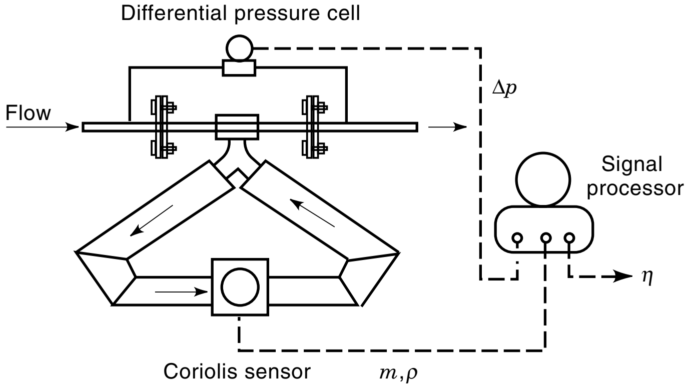

Figure 6. Schematic diagram of an on-line capillary–Coriolis viscometer geometry. The Coriolis sensor measures the mass flow rate m and the density ρ while the differential-pressure cell measures the pressure drop Δp. A signal processor combines the three measurements to produce the viscosity output η.

Glass Capillary Viscometers. Pressure-flow viscometers featuring a glass capillary, such as the Cannon, Ostwald, and Ubbelohde viscometers, have been used for many years in off-line environments to measure the viscosity of Newtonian fluids. Since in these devices the pressure driving force is supplied by the fluid head, the instruments measure the kinematic viscosity. The principle of measurement consists of determining the time needed for a given volume of fluid to pass through the glass capillary. This lapse of time is known as the *time of efflux,* and can be used to calculate the kinematic viscosity via the equation

$$\nu = \phi_1 t + \frac{\phi_2}{t} \tag{16}$$

where ϕ is the kinematic viscosity, ρ is the density, t is the time of efflux, and ϕ_1 and ϕ_2 are constants determined by calibration against fluids of known viscosity. These glass capillary viscometers are useful for Newtonian fluids only. Usually, the instrument is used to measure viscosities of fluids for which the term ϕ_2/t is negligible.

Specialized Capillary Viscometers. Specialized pressure-flow viscometers that carry out measurements under conditions specified by standards organizations have been used for many years for specific materials. For example, the *Zahn cup,* a fluid-head device with an extremely short L/D ratio, has been used to control the viscosity of paints, inks, dyes and other materials as specified by ASTM D4212-93 (1990). Also, the *Saybolt viscometer,* a device with a short L/D ratio, incorporates a load-bearing plunger on the chamber containing the fluid to add a significant pressure difference to the fluid head. The time for a known volume of fluid to be forced through the capillary under the specified load is measured, and the viscosity is reported in arbitrary time units commonly referred to as *Saybold viscosity units.* Specifications for the test are given in ASTM D1238-90b (1990). Saybolt viscometers have been used so extensively that tables for converting Saybolt viscosity measurements to poise and other conventional units have been developed for Newtonian fluids and can be found in standard references (20).

Another important specialized viscometer of pressure-flow type is the *melt indexer,* which is used extensively for polymer melts. The melt contained in the viscometer chamber is driven through a capillary of small L/D by a fixed load to give a constant pressure difference. The measured mass of polymer that flows through the capillary in a specified period of time is determined, and is reported in grams as the *melt index* (or *melt flow* for some polymers). Complete specifications for the use of this instrument are given in ASTM D445-88 (1990).

Vibrational Viscometers

Vibrating elements immersed in a fluid can be used to measure the viscosity, because the energy required to sustain a given frequency and amplitude of oscillation depends upon the viscosity of the fluid. A wide variety of vibrational viscometers, which differ primarily in the geometry of the vibrating element, have been developed. The most commonly used elements are spherical or cylindrical probes, as well as wires, rods, or plates. The vibrating element is fixed at one end, allowing motion about a pivotal point. Typically, the element is made to oscillate by an induced magnetic force. Vibrational viscometers are used in a variety of industries, due to their versatility.

The principle of operation of these instruments is based upon either controlling the amplitude or the frequency of oscillation of the element. In an amplitude-controlled vibrational viscometer, a force is applied to the element in such a way as to make it oscillate at a high frequency but at constant amplitude. The power required to maintain a particular amplitude is directly related to the viscosity (21). For a given amplitude, the power required increases as the viscosity of the sample increases. Frequency-controlled viscometers operate using an analogous principle, but keep the frequency at a user-specified constant value.

The physics of oscillation of a spherical probe in a fluid medium at a constant amplitude is described by the equation (6)

$$\eta = \tfrac{1}{2}\delta^2\omega^2\rho^2 \tag{17}$$

where ω is the vibrational frequency that yields the required amplitude, ρ is the density of the fluid, and δ is the distance the oscillatory wave propagates through the sample medium until its amplitude falls to $1/e$ of its original level, where e is the base of natural logarithms. Therefore, there is a fundamental relationship between the viscosity and the frequency. The specific governing equation for a practical viscometer must take into account a number of additional factors, including the geometry of the vibrating elements as well as the compartment size in which the element vibrates. Note that for a spherical probe the mass of the vibrating element can be considered to be concentrated at a point, whereas for a vibrating rod the mass is distributed throughout the entire element.

A commercial vibrational viscometer for in-line or on-line use, produced by the Nametre Company, is shown in Fig. 7. The vibrating sensor is located inside the measuring chamber. The fluid flows past the instrument from the bottom, after colliding with a deflector plate that protects the sensor from direct fluid impact. The material flows through the chamber and exits through the outlet port at the top of the instrument. The instrument can be fitted with a heating jacket in order to maintain a constant temperature. The Nametre Company viscometer operates on an controlled-amplitude mode; hence, under normal operation, the transducer that causes the sensor to vibrate is driven in such a way that the amplitude of motion of the sensor is held constant at approximately 1 μm, and the average electrical power P required to accomplish this constant amplitude is measured. It can be shown that the product of the viscosity of the fluid times its density is given by the expression

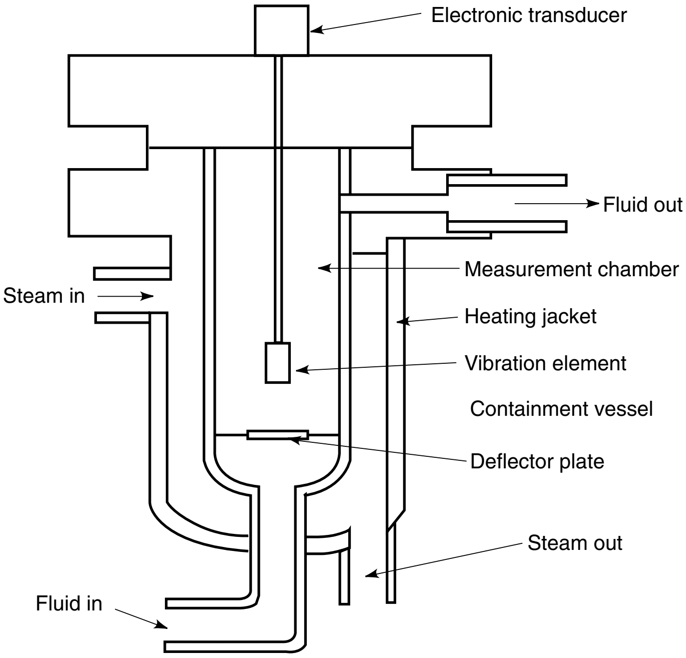

Figure 7. Schematic of an in-line vibrational viscometer. The power required to maintain the vibration element at a constant amplitude is related to the viscosity.

$$\eta\rho = \frac{2}{\omega}\frac{P^2}{\phi} \tag{18}$$

where η is the viscosity, ρ is the density, ω is the frequency of vibration, P is the power, and ϕ is an experimental factor specified by the manufacturer and stored in the instrument's on-board electronics. Note that the viscosity of the fluid can be obtained from the viscosity–density product measured by the instrument if the density of the material is known or is measured using an on-line densitometer. The shear rate is given by $\dot{\gamma} = \omega$, where ω is measured in radians per second. Equation (18) gives accurate estimates of the viscosity–density product of fluids that do not show viscoelastic behavior, such as Newtonian fluids, for example. When the sample fluid is viscoelastic, the viscosity appearing on the left-hand side of Eq. (18) is interpreted as a *nominal viscosity* because it is affected by the energy-storage behavior of the elastic modes of the fluid.

Vibrational viscometers for on-line measurements are marketed by a number of companies. These devices can also be used for laboratory measurements. In particular, Nametre Company, BTG, and Dynatrol market vibrational viscometers. The measurements are fairly independent of the flow rate of the fluid being measured; in fact, the flow can even be moderately turbulent. Most instruments operate at a single frequency of oscillation, hence they operate at a single shear rate, a disadvantage when characterizing the flow of non-Newtonian fluids. During operation of the instrument, extreme care must be taken to keep the vibrating element free of deposits that could affect the total mass of the element and lead to biased measurements.

Challenges in On-Line Viscosity Measurement

On-line measurements using the traditional principles of operation introduce many technical challenges, and appropriate remedial measures are necessary to obtain reliable measurement and control. The problems and solutions depend on the particular process at hand. For example, if a rotational device is used, with a superimposed axial flow, a spiral flow within the instrument results, and this can introduce errors in measurement at high flow rates. If a capillary–Coriolis device is used, the flow rate must be high enough to produce an appreciable pressure drop between the points of measurement, but the flow regime must still be laminar. With a falling-element device, axial flow can force the falling element to hit the wall of the instrument, and this can result in malfunction of the instrument. There is also the possibility of corrosion of the equipment or deposits on elements of the instrument due to continued exposure to the process conditions. This can change critical dimensions or change the response of measuring elements.

These are problems of a general nature. In addition, every application gives rise to a unique set of challenges. For example, preserving the phase distribution of the sample in a multiphase flow (as in suspensions, slurries, and pastes) during measurements is a major challenge.

Reported Applications of On-Line Viscometers

Many application studies have been reported in the literature on using in-line and on-line viscometers in process industries. The following abridged list gives an overview into the range of applications of on-line viscometers. See Table 2 for an overview of commercial in-line and on-line viscometers available in the market, and Table 3 for contact information. Kalotay (19) and Bates (22) discuss the principles and various applications of on-line capillary–Coriolis and on-line rotational viscometers, respectively, for measurement and control. See also De Laney et al. (23). Esseghir et al. (24) discuss the development of in-line and on-line sensors to monitor blend rheology and morphology for microstructure monitoring in compounding polymer blends. Baker et al. (25) discuss an on-line rheometer to monitor the change in melt index of polymer products. Broadhead et al. (26) used an in-line rheometer for closed-loop viscosity control of reactive extrusion. Kawatra et al. (27) studied the effect of slurry viscosity on hydroclone classification by installing an on-line viscometer on a hydroclone system. Shi and Napier-Munn (28) have developed a new procedure for obtaining a full shear-rate–shear-stress curve by using an on-line viscometer. Kawatra and Bakshi (29) have used vibrating-sphere and rotational on-line viscometers for measurements on mineral suspensions. Pillo et al. (30) describe using a viscometer in closed-loop control of recycled high-density polyethylenes during extrusion; the melt viscosity was measured with an on-line rheometer and used as the indicator of polymer quality. Speight et al. (31) use in-line process viscosity monitoring for injection molding control.

The advantages of using an on-line viscometer are also being realized in the food and the pulp and paper industries. For example, in the manufacture of skim milk powder, it is known that using an on-line viscometer to control the degree of evaporation leads to a significant reduction of steam consumption and stack losses, and to the minimization of fouling problems (32). Furthermore, maintaining a constant viscosity also results in a more consistent product, as the mean powder particle diameter is known to be directly proportional to the viscosity of the skim milk concentrate (33).

It is also known that using on-line viscometers in the pulp and paper industry can assist in obtaining enormous energy savings, and studies have been done to evaluate various principles of viscosity measurement (34,35) for this purpose.

Future Developments

There are continuing efforts to develop new types of on-line rheometers for various applications. For example, see Todd et al. (36) for a helical-barrel rheometer, and Arola et al. (37) for an NMR-based method in which nuclear magnetic resonance imaging and fundamental principles of capillary flow are combined.

Rapid advances in the development of viscometers have been made in the last two decades, and the pace of development and applications is accelerating, as is seen from the examples cited. However, much more is needed. The viscosity range that is of interest for industrial fluids varies by about five orders of magnitude. Also, the rheology of the fluid is an additional complication. Technology is available now for accurate on-line measurement of Newtonian, single-phase fluids and for time-independent non-Newtonian single phase fluids. However, accurate measurements can be made now for only a limited number of multiphase fluids, and time-dependent viscosity is extremely difficult (virtually impossible) to measure on line at present. Corrosive process conditions add to the complexities.

On-line viscometers are moderately expensive devices. That they are nonetheless being adapted for measurement and control in such a diverse array of industries is the best indication of their potential value.

IMPORTANT ISSUES IN VISCOSITY MEASUREMENT AND CONTROL

Challenges Posed by Non-Newtonian Fluids

Incompressible Newtonian fluids at constant temperature are completely characterized by two *material constants:* density and viscosity. For non-Newtonian fluids the rheology leads to *material functions* that are dependent on shear rate, frequency, composition, and time (3). These complexities make it significantly more difficult to measure and control the rheological properties of non-Newtonian materials. However, a wide class of industrially important materials such as polymer solutions, polymer melts, motor oils, varnishes, adhesives, coatings, paints, and foods are non-Newtonian.

From an application viewpoint, the most important rheological property is the non-Newtonian viscosity. Viscosity has very significant effects on heat transfer, fluid transport, droplet and bubble formation and breakup, foaming, lubrication, coating and calendering, extrusion, mixing, and molding, just to mention a few commercially important operations. Proper measurement of viscosity on line can lead to major improvements in these operations and processes.

In addition, the viscosity of the fluid is an important performance specification for the final product. Direct on-line measurement can lead to vastly improved control of product uniformity. This possibility is particularly important for foods, coatings, and lubricants. It is, of course, complicated by the wide range of viscosity exhibited by industrially important fluids. Even a single fluid can exhibit very large variations in viscosity during processing due to temperature, concentration, and shear-rate changes. For example, Kraft black liquor obtained from pulping only one wood species can vary in viscosity by more than three orders of magnitude in the course of processing (38–41). At high concentration, the viscosity of such liquors can vary by more than an order of magnitude at the same temperature, concentration, and shear rate due to variations in composition and interaction of the constituents. This is not uncommon for concentrated solutions or suspensions derived from natural sources.

The phenomenological behavior of any one of these complex fluids is uniform, even though the viscosity varies widely. Various theories proposed to explain the rheological behavior of non-Newtonian fluids have led to models of varying complexity, ranging from generalized Newtonian models such as the power-law model (3), the Cross model (42), and the Carreau–Yasuda model (43,44), to more complex nonlinear viscoelastic models (3). These models yield the general response. For limited ranges of shear rate, two measurements in the shear-sensitive region can be used to define the viscosity behavior. Thus, it is possible to control the viscosity of Newtonian and simple non-Newtonian time-independent fluids with one or two on-line measurements if the general rheological behavior of the fluid is known.

Challenges Posed by Multiphase Fluids

The problem of measuring viscosity is more challenging in the case of multiphase materials. The shear-rate-dependent viscosity and the flow behavior change markedly with phase distribution and particle size distribution. Many industrially important products are in this category. Examples include milk products, mayonnaise, peanut butter, unleavened dough, chocolate, cheese spreads, latex paints, and coating materials such as inks and paints. Measurement is usually difficult, and on-line control is virtually impossible. For example, see Kawatra and Bakshi (45) for an extensive discussion of various problems involved in the on-line measurement of slurry viscosity using rotational, capillary, and vibrational viscometers. However, if the slurry can be shown to behave as a bulk fluid by obtaining off-line measurements made in different viscometer geometries that are in agreement with each other, on-line measurement and control is possible.

Challenges Posed by Fluids with Time-Dependent Viscosity

A third major challenge is time dependence of the viscosity of materials. For example, the viscosity of tomato juice decreases with time of shearing, whereas that of egg white increases. The usual approach to this problem is to measure viscosity under identical and controlled conditions in the laboratory. On-line measurement and control is still an open issue.

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